# Past-paper walk-through

Catalysis ▪ 5.11

eXercise

# Questions in this set

- 2025 Q7
- 2021 Q1

# Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

# Question 7

2025 ▪ Q7

Answer the following questions about the glycolate ion, $C_2H_3O_3^-$, which acts as a base in aqueous solution. A Lewis diagram for the ion is provided.
[Lewis structure of the glycolate ion in brackets with an overall negative charge: H—O—C(—H)(—H)—C(=O)—O:, i.e., an H atom bonded to an O atom (with two lone pairs) which is bonded to a C atom; that C atom is bonded to two H atoms and to a second C atom; the second C atom is double-bonded to an O atom (with two lone pairs) above it and singly bonded to another O atom (with three lone pairs) on the right.]
**(a)** On the Lewis diagram in part A, circle the atom that accepts the proton when the glycolate ion reacts with water.
When the glycolate ion reacts with water, it forms glycolic acid, $HC_2H_3O_3$, according to the following equation. The $K_b$ expression for the reaction is provided.

## Question 7

$$C_2H_3O_3^-(aq) + H_2O(l) \rightleftharpoons HC_2H_3O_3(aq) + OH^-(aq) \qquad K_b = \frac{[HC_2H_3O_3][OH^-]}{[C_2H_3O_3^-]}$$

# Question 7

2025 ▪ Q7

Answer the following questions about the glycolate ion, $C_2H_3O_3^-$, which acts as a base in aqueous solution. A Lewis diagram for the ion is provided.

[Lewis structure of the glycolate ion in brackets with an overall negative charge: H—O—C(—H)(—H)—C(=O)—O:, i.e., an H atom bonded to an O atom (with two lone pairs) which is bonded to a C atom; that C atom is bonded to two H atoms and to a second C atom; the second C atom is double-bonded to an O atom (with two lone pairs) above it and singly bonded to another O atom (with three lone pairs) on the right.]

**(b)** At $25°$C, a 2.5 $M$ solution of glycolate is found to have $[OH^-] = 1.3 \times 10^{-5}$ $M$.

**(b)(i)** Calculate the value of $K_b$ for the glycolate ion.

**(b)(ii)** Using your answer to part B (i), calculate the value of $K_a$ for glycolic acid at $25°$C.

# Question 7

Glycolic acid can be produced from the hydrolysis of methyl glycolate, $C_3H_6O_3$. A proposed mechanism for the reaction is given.

Step 1: $C_3H_6O_3 + H_3O^+ \rightleftharpoons C_2H_5O_3^+ + CH_3OH$

Step 2: $C_2H_5O_3^+ + H_2O \rightleftharpoons HC_2H_3O_3 + H_3O^+$

Overall: $C_3H_6O_3 + H_2O \rightleftharpoons HC_2H_3O_3 + CH_3OH$

# Question 7

2025 ▪ Q7

Answer the following questions about the glycolate ion, $C_2H_3O_3^-$, which acts as a base in aqueous solution. A Lewis diagram for the ion is provided.

[Lewis structure of the glycolate ion in brackets with an overall negative charge: H—O—C(—H)(—H)—C(=O)—O:, i.e., an H atom bonded to an O atom (with two lone pairs) which is bonded to a C atom; that C atom is bonded to two H atoms and to a second C atom; the second C atom is double-bonded to an O atom (with two lone pairs) above it and singly bonded to another O atom (with three lone pairs) on the right.]

**(c)** A student claims that $H_3O^+$ is a catalyst for the reaction. Do you agree or disagree? Justify your answer based on the mechanism given.

# Solution 7

## (a)

**Mark scheme**

- Circle one of the two equivalent terminal oxygen atoms on the carboxylate ($-COO^-$) group of the glycolate ion — the atom that accepts the proton ($H^+$) from water to form glycolic acid. Because of resonance, the two C–O bonds on the carboxylate group are equivalent, so circling either one is acceptable.

# Solution 7

**(b)**

**Mark scheme**

- No separate response required — this is the context/stem giving $[\mathrm{OH}^-] = 1.3 \times 10^{-5}$ *M* for a 2.5 M glycolate solution at $25°$C that parts (i) and (ii) below use.

# Solution 7

## (b)(i)

**Mark scheme**

- $K_b = \dfrac{[\mathsf{HC_2H_3O_3}][\mathsf{OH^-}]}{[\mathsf{C_2H_3O_3^-}]} = \dfrac{(1.3 \times 10^{-5})(1.3 \times 10^{-5})}{2.5 - 1.3 \times 10^{-5}} \approx \dfrac{(1.3 \times 10^{-5})^2}{2.5} = 6.8 \times 10^{-11}$.

# Solution 7

## (b)(ii)

### Mark scheme

- $K_a = \dfrac{K_w}{K_b} = \dfrac{1.0 \times 10^{-14}}{6.8 \times 10^{-11}} = 1.5 \times 10^{-4}$ (using the $K_b$ value from part B(i)).

# Solution 7

## (c)

### Mark scheme

- Agree. $H_3O^+$ is consumed in step 1 of the mechanism and regenerated in step 2, which is consistent with the behavior of a catalyst — it is used up and then reformed, so it is not permanently consumed by the overall reaction.

# Question 1

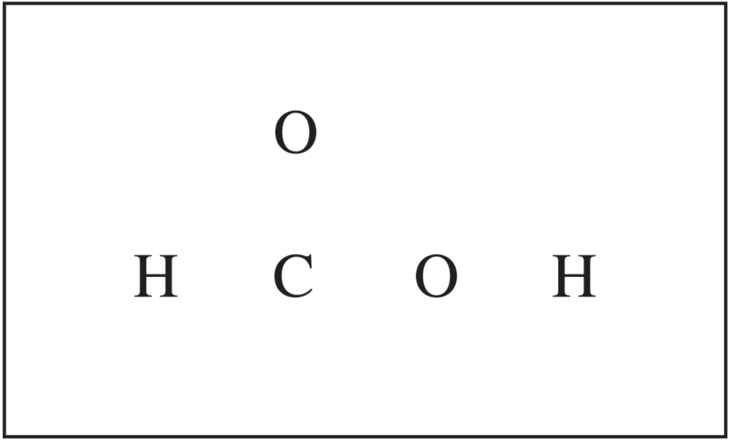
2021 ▪ Q1

$$\mathrm{HCOOH}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{HCOO^-}(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

**(a)** Write the expression for the equilibrium constant, $K_a$, for the reaction.

# Question 1



# Question 1

2021 ▪ Q1

$$\mathrm{HCOOH}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{HCOO^-}(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

**(b)** Calculate the pH of a 0.25 *M* solution of HCOOH.

# Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

**(c)** In the box below, complete the Lewis electron-dot diagram for HCOOH. Show all bonding and nonbonding valence electrons.

[Box containing the skeletal atom arrangement of HCOOH (no bonds or lone pairs drawn), laid out as:

```
        O
        |
H - C - O - H
```

# Question 1

i.e. a central C bonded to: an O atom above it (drawn separated, no bond line shown), an H atom to its left, and an O atom to its right which is in turn bonded to a further H atom on the far right. The student must add all bonding and nonbonding valence electrons to complete the Lewis structure.]

# Question 1

2021 ▪ Q1

$$\mathrm{HCOOH}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{HCOO^-}(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

**(d)(i)**

$$\mathrm{H_2NNH_2}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_2NNH_3^+}(aq) + \mathrm{OH^-}(aq) \qquad K_b = 1.3 \times 10^{-6}$$

In aqueous solution, the compound $H_2NNH_2$ reacts according to the equation above. A 50.0 mL sample of 0.25 $M$ $H_2NNH_2(aq)$ is combined with a 50.0 mL sample of 0.25 $M$ $HCOOH(aq)$.

Write the balanced net ionic equation for the reaction that occurs when $H_2NNH_2$ is combined with HCOOH.

**(d)(ii)** Is the resulting solution acidic, basic, or neutral? Justify your answer.

# Question 1

2021 ▪ Q1

$$\mathrm{HCOOH}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{HCOO^-}(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

**(e)** When a catalyst is added to a solution of HCOOH($aq$), the reaction represented by the following equation occurs.

$$\mathrm{HCOOH}(aq) \rightarrow \mathrm{H_2}(g) + \mathrm{CO_2}(g)$$

Is the reaction a redox reaction? Justify your answer.

# Question 1

2021 ▪ Q1

$$\text{HCOOH}(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{H}_3\text{O}^+(aq) + \text{HCOO}^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

**(f)** [Graph: Total Pressure (atm) on the y-axis (from 0 to above 24, with a dashed horizontal line at 24) vs. Time (hours) on the x-axis. The curve rises steeply from the origin, curving and leveling off asymptotically to a plateau at a total pressure of 24 atm.]

The reaction occurs in a rigid 4.3 L vessel at 25°C, and the total pressure is monitored, as shown in the graph above. The vessel originally did not contain any gas. Calculate the number of moles of $CO_2(g)$ produced in the reaction. (Assume that the amount of $CO_2(g)$ dissolved in the solution is negligible.)

# Question 1

2021 ▪ Q1

$$\mathrm{HCOOH}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{HCOO^-}(aq) \qquad K_a = 1.8 \times 10^{-4}$$

Methanoic acid, HCOOH, ionizes according to the equation above.

**(g)** After the reaction has proceeded for several minutes, does the amount of catalyst increase, decrease, or remain the same? Justify your answer.

# Solution 1

## (a)

**Mark scheme**

- $K_a = \dfrac{[H_3O^+][HCOO^-]}{[HCOOH]}$ — the correct equilibrium-constant expression for the dissociation of HCOOH (products over reactant; water omitted as pure liquid).

# Solution 1

## (b)

**Mark scheme**

- ICE table for HCOOH + H2O   H3O+ + HCOO-, initial [HCOOH]=0.25 M: $K_a = 1.8 \times 10^{-4} = \dfrac{x^2}{0.25 - x}$. Assuming $x \ll 0.25$: $x^2 = (1.8 \times 10^{-4})(0.25) \Rightarrow x = [\mathrm{H_3O^+}] = 0.0067\ M$ (1 pt). Then $\mathrm{pH} = -\log[\mathrm{H_3O^+}] = -\log(0.0067) = 2.17$ (1 pt, consistent with the calculated concentration).

# Solution 1

## (c)

**Mark scheme**

- Correct complete Lewis structure of HCOOH (formic acid): H–C(=O)–O–H. The central C is bonded to: an H atom (single bond), a terminal O by a double bond (that terminal O carries 2 lone pairs), and a second O by a single bond (that O carries 2 lone pairs and is also single-bonded to the second H). All bonding pairs and all nonbonding (lone) pairs of valence electrons must be shown explicitly.

# Solution 1

## (d)(i)

**Mark scheme**

- $H_2NNH_2(aq) + HCOOH(aq) \rightarrow H_2NNH_3^+(aq) + HCOO^-(aq)$ — the weak base H2NNH2 accepts a proton from the weak acid HCOOH; already balanced as written (state symbols not required).

# Solution 1

## (d)(ii)

### Mark scheme

- Acidic. The resulting solution is a mixture of the conjugate acid H2NNH3+ and the conjugate base HCOO-. Because the $K_a$ of $H_2NNH_3^+$ is greater than the $K_b$ of $HCOO^-$, production of $H_3O^+(aq)$ occurs to a greater extent than production of $OH^-(aq)$, so the solution is acidic.

# Solution 1

## (e)

**Mark scheme**

- Yes, it is a redox reaction. Accept either valid justification: the oxidation number of hydrogen changes from +1 in HCOOH to 0 in H2 (reduction); or the oxidation number of carbon changes from +2 in HCOOH to +4 in CO2 (oxidation).

# Solution 1

## (f) Mark scheme

- Reaction HCOOH(aq) $\rightarrow$ H2(g) $+$ CO2(g) produces H2 and CO2 in a 1:1 mole ratio, so each contributes half the total pressure:
  $P_{CO_2} = 24\text{ atm} \times \dfrac{1\text{ atm } CO_2}{2\text{ atm product}} = 12\text{ atm}$ (1 pt, may be implicit). Then using the ideal gas law $PV = nRT$ with V=4.3 L, T=298 K:
  $n = \dfrac{PV}{RT} = \dfrac{(12\text{ atm})(4.3\text{ L})}{(0.08206\text{ L}\cdot\text{atm}\cdot\text{mol}^{-1}\text{K}^{-1})(298\text{ K})} = 2.1\text{ mol } CO_2$ (1 pt).

# Solution 1

## (g)

### Mark scheme

- It would remain the same. In a catalyzed reaction the catalyst is not consumed — it participates in the mechanism but is regenerated — so the net amount of catalyst present stays constant over time.